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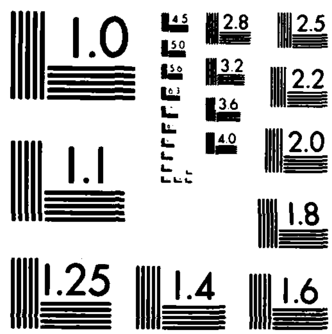

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PREDICTIVE MODEL OF ELECTRON BEAM INDUCED FLASHBLINDNESS

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Thomas G. Wheeler, Ph.D.

March 1985

Final Report for Period November 1983 – October 1984

USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
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NOTICES

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The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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The spectral characteristics of the Cerenkov radiation have been evaluated and converted to equivalent retinal irradiance from external sources. On the basis of the conversion, electron fluxes have been estimated for 2-sec recovery times from flashblindness. The electrons are assumed to have energies >6 MeV and to be delivered in one or more bursts of 1 µsec each over 1 sec. It is important to note that very little data exists on recovery times as short as 2 sec for either photopic or scotopic conditions. This situation is a direct result of the lack of definition of the critical tasks and their sensitivity to an interruption of background adaptation.

The Cerenkov radiation produced within the eye by relativistic electrons can be compared to light from external sources by the relationships:

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19. ABSTRACT (continued)

$$1 \text{ rad} \approx 4.6 \text{ scotopic td·sec}$$

and

$$1 \text{ rad} \approx 0.55 \text{ photopic td·sec}$$

Based on these conversion factors, the following estimates can be derived by extrapolation from existing data:

1. Absolute threshold is equivalent to the Cerenkov radiation from a 4.3-μrad electron beam and to a 0.5-mrad x-ray beam.

2. For low photopic levels of adaptation (approximately 10 td), 10^5-rad electron beam would be required for a 2-sec recovery time for foveal or parafoveal vision.

3. For the dark-adapted eye, a dose of 10 rads may cause a 2-sec interruption in the detection of low-contrast, peripheral targets.

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INTRODUCTION

When high-energy particles traverse a dielectric, the medium is polarized and electromagnetic radiation is produced. If the particle velocity is greater than the velocity of light in the medium, the radiation will undergo constructive interference and travel in the forward direction at zero angle with the direction of the particle. The condition for constructive interference results in the relation

$$\cos 0 = v_\lambda / v_o \,, \tag{1}$$

where v_λ is the velocity of light in the medium, c/n_λ, and v_o is the velocity of the particle. The light produced is called Cerenkov radiation for the scientist who first described the underlying mechanism. Subsequent work by Frank and Tamm (1) resulted in quantitative relationships for the calculation of the spectral distribution and the total radiant energy per unit path length.

The purpose of this study is to consider the effect on visual performance of the Cerenkov radiation produced by a beam of electrons with energies of a few megaelectronvolts or greater. Specifically, consideration will be given to the feasibility of applying the existing data on flashblindness to predict visual performance following microsecond exposures to the electron beam. The problem proposed is important in view of the current development of particle beam accelerators. The major complexity of the problem is that the Cerenkov radiation produced within the eye has different spectral and spatial characteristics from any that can be produced by external sources.

Practically all of our current knowledge of flashblindness phenomena is based on experimental work performed with high-intensity flashes from external "white" light sources. Such externally produced light is filtered by the ocular media before impinging on the retina. The cornea and lens absorb strongly below 400 nm. The optical system of the eye limits the angle of incidence on the retina to within a few degrees of the axis of the receptors. The shortest exposures used in flashblindness studies have been of the order of 100 μsec, and there is some danger in extrapolating the results to the 1-μsec range. In view of these facts, it is obvious that there are serious practical difficulties in applying our presently available flashblindness data to the significantly different conditions encountered with Cerenkov radiation.

CHARACTERISTICS OF CERENKOV RADIATION

The kinetic energy of particles accelerated to relativistic velocities is given by:

$$T = m_o c^2 \{-1 + 1/\sqrt{1 - \beta^2}\} \tag{2}$$

where c is the vacuum velocity of light, 2.998×10^8 m/sec, m_o is the rest mass of the particle, and β is the ratio of the velocity of the particle to the vacuum velocity of light,

$$\beta = v_o/c \tag{3}$$

The conditions for constructive interference of the light emitted while a charged particle moves through a dielectric medium require that the particle velocity be greater than that of light in the medium. The velocity of light in a medium of index of refraction n is

$$v_\lambda = c/n_\lambda \tag{4}$$

The subscript λ is used because all optical media exhibit dispersion or a variation of index of refraction with wavelength. From equations (3) and (4), constructive interference will result in Cerenkov radiation when

$$\beta > 1/n. \tag{5}$$

The threshold energy for Cerenkov radiation can be found from equations (2) and (5) for an electron traversing the eye. The rest mass of an electron is 9.1×10^{-31} kg, making the electron mass energy,

$$m_e c^2 = 0.5106 \text{ MeV}. \tag{6}$$

The indices of refraction of the ocular media range from approximately that of water at 36 °C to a maximum of about 1.42 for sodium light for the center of the lens. The aqueous and vitreous humors, which account for approximately 90% of the total volume of the globe, have the lowest index of refraction. The indices of the various ocular media as a function of wavelength are shown in Figure 1. Using the inverse of the lowest index of refraction for β (equation 5) and substituting in equation 2, we find that the threshold energy for the production of Cerenkov radiation by electrons in the eye is 0.2623 MeV.

The direction of light travel is at zero angle with the direction of the particle, and the conditions for constructive interference yield the relationship

$$\cos \theta = 1/\beta n. \tag{7}$$

From this relationship, we can calculate the half angle of the cone of light formed as an electron traverses the eye. The half angles are shown in Figure 2 for n_D for the aqueous and vitreous humors and for the central lens as a function of the electron energy. For energies above a few MeV, $\beta \cong 1$ and the cone half angles are a maximum.

Frank and Tamm (1) derived the quantitative relationships for the total energy radiated in a short element of the particle path. Stated in terms of the number of quanta radiated in 1 cm of path length in a wavelength interval $\Delta\lambda$, the intensity is

$$I = \frac{4\pi^2 z^2 e^2}{hc} \quad \frac{1}{\lambda_1} - \frac{1}{\lambda_2} \quad 1 - \frac{1}{\beta^2 n^2} \; . \tag{8}$$

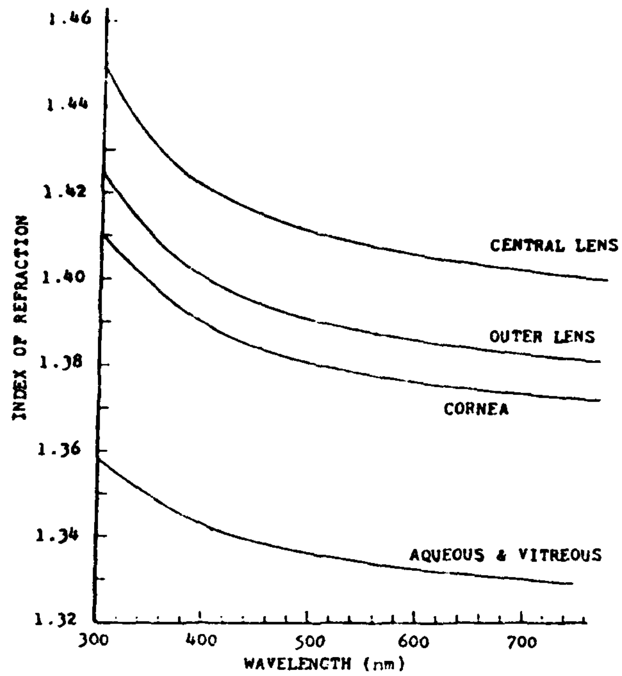

Figure 1. The index of refraction of the ocular media (2).

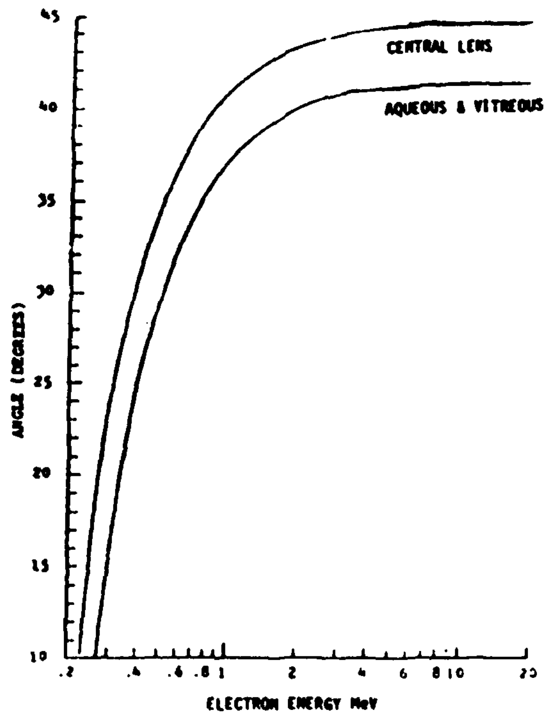

Figure 2. The angle between the Cerenkov radiation and the direction of travel of an electron through the ocular media as a function of the electron energy.

Substituting the values: $z = -1$, $e = 4.8 \times 10^{-10}$ e.s.u., $h = 6.625 \times 10^{-27}$ erg·sec, $c = 2.998 \times 10^{10}$ cm/sec, and cos 0 for $1/\beta n$; the number of quanta per cm of path length for electrons is

$$I = \frac{2\pi\Delta\lambda}{137\lambda^2} \sin^2 0, \tag{9}$$

where λ is the central wavelength in the interval in cm. The equation indicates that the number of quanta per constant wavelength interval varies as the inverse square of the central wavelength. This fact, together with the increasing index of refraction with decreasing wavelength, results in a spectral distribution rich in short wavelengths.

The spectral distributions for the aqueous and vitreous humors and central lens are shown in Figure 3 for electron energies of about 6 MeV or greater; that is, for electron velocities close to the vacuum velocity of light. The distributions have been calculated for the wavelength range from 300 to 760 nm. Pinegin (3) reported that all of his subjects could see 305 nm if the intensity was sufficiently high and if the chromatic aberration of the eye was corrected. The crystalline lens absorbs strongly below 380 nm, so we usually consider the limits of the visible spectrum to be about 380 to 760 nm. It is interesting to note from the values in Figure 3, that around 42% of the total quanta in the range are in the wavelength interval from 300 to 400 nm.

PHOTOMETRY OF EXTERNAL SOURCES

For an adequate comparison of the effects of Cerenkov radiation on visual performance with the experimentally determined flashblindness data, we must consider the characteristics of the external flash sources and the transmission of the eye. It is appropriate to review the definitions of the basic photometric units. The photopic and scotopic luminosity factors adopted by the Commission Internationale de l'Eclairage (CIE) in 1932 and 1951 provided the standardized values for the effectiveness of radiant power at each 5-nm wavelength interval from 380 to 760 nm. The luminosity factors have been experimentally determined and referred to the light used by the retina in producing a sensation of brightness; that is, both the absorption of the ocular media and the action spectra of the retinal photopigments are included in them. The scotopic curve, peaking at 507 nm, and the photopic curve, peaking at 555 nm, refer to rod vision and cone vision respectively.

The luminosity factors are used in converting radiometric quantities (watts) to photometric quantities (lumens) through the definition of the candela (cd). The physical standard for the photometric units is a blackbody at the freezing point of platinum. By definition, such a blackbody has a luminance of 60 cd/cm^2. The blackbody radiation laws give a precise description of the spectral radiance and total radiant power from such a source. By summing the products of the luminosity factor and radiant power in each wavelength interval and equating to 60 cd/cm^2, the values of 1750 scotopic lumens per watt at 507 nm and 680 photopic lumens per watt at 555 nm are found. In like manner the luminance of any radiating or reflecting surface can be found from its spectral radiance distribution.

As an example, we can calculate the luminous flux from a xenon flash tube for both rod and cone response. The xenon flash is the most commonly used

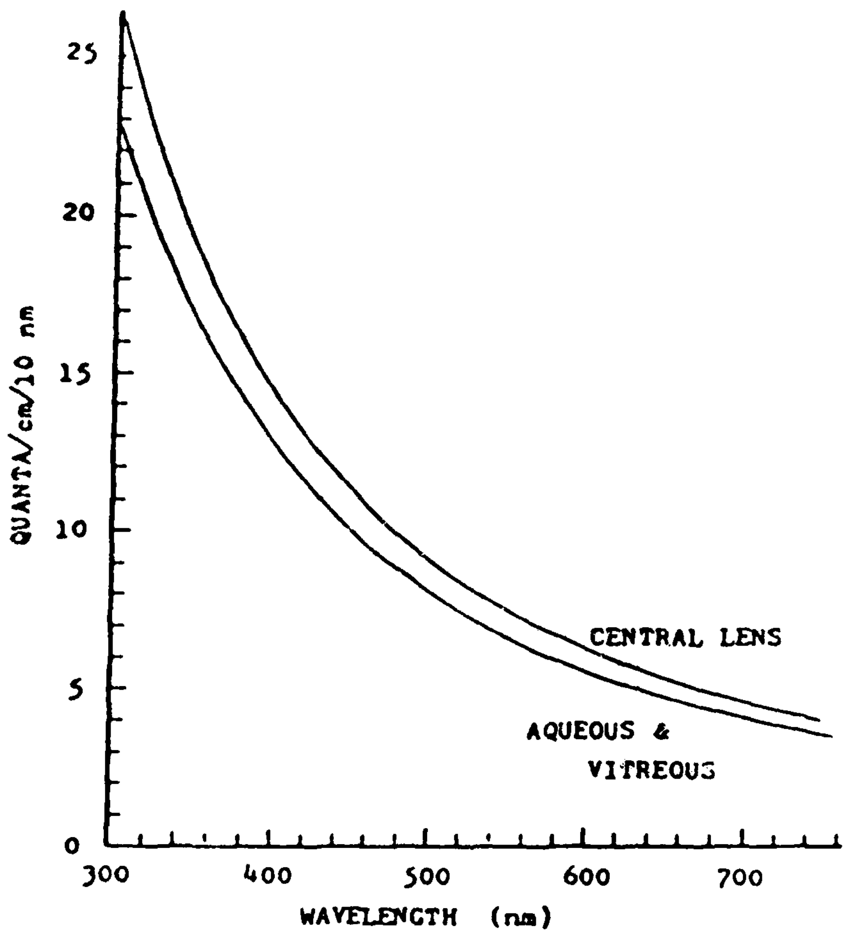

Figure 3. The number of quanta per centimeter of path length per 10-nm band produced in the ocular media by an electron of 6 MeV or greater.

source for flashblindness studies. Figure 4 shows a typical spectral steradiancy distribution for such a source filtered through an optical system and an infrared absorbing filter. The two lower curves are the equivalent watts of 507 and 555 nm for each wavelength; the glass in the optical train absorbs most of the energy below 400 nm. This distribution accounts for the difficulty in comparing the effects of Cerenkov radiation with flashblindness data from external sources.

A useful unit in dealing with problems of retinal events is the troland, a unit of retinal illuminance. The unit involves knowledge of the pupil area so it is especially useful with Maxwellian view systems in the laboratory. The unit is also useful for evaluating the effects of flashes delivered against steady-state conditions of known luminance levels. The troland (td) is defined as the retinal illuminance from a surface of 1 cd/m^2 viewed through 1 mm^2 of pupil area, or the td is equivalent to 10^{-6} lumens per steradian of visual angle. This value can be converted to the number of quanta per steradian per second corresponding to 1 td:

$$1 \text{ scotopic td} = 1/1750 \text{ equiv. watts of } 507 \text{ nm} \qquad (10)$$

and substituting the value of the energy of 1 quantum,

$$1 \text{ scotopic td} = 1.46 \times 10^9 \text{ q/sec/sr of } 507 \text{ nm} \qquad (11)$$

In like manner,

$$1 \text{ photopic td} = 4.11 \times 10^9 \text{ q/sec/sr of } 555 \text{ nm.} \qquad (12)$$

It is helpful to examine the luminance values found in some common lighting situations to gain an appreciation of the magnitude of the units. In Table 1, a range of luminance levels is listed with the retinal illuminances based on average pupil diameters for the conditions of viewing. The absolute threshold for large fields (5,6) corresponds to one quanta of 507 nm at the cornea for 900 rods. At cone threshold, this quantity rises to 3 quanta per rod.

TABLE 1. THE AVERAGE LUMINANCE VALUES AND RETINAL ILLUMINANCES FOR A VARIETY OF COMMONLY ENCOUNTERED SITUATIONS. IN THE CONDITIONS MARKED RODS, THE RETINAL ILLUMINANCE IS IN SCOTOPIC TROLANDS.

Condition	Luminance cd/m^2	Retinal illuminances td
Absolute threshold (rods)	7.3×10^{-7}	3.7×10^{-5}
Darkest night sky (city)(rods)	1.4×10^{-5}	6.8×10^{-4}
Snow in starlight (rods)	3×10^{-4}	1.6×10^{-2}
Cone threshold--color appears	3×10^{-3}	.1
Snow or cloud tops in full moon	3×10^{-2}	1
Snow - 40 min past sunset	.32	5.6
Light object - average interior (night)	10^2	10^3
Blue sky well away from sun	10^3	4.6×10^3
Snow or cloud tops in full sun	10^4	3.7×10^4
Sun at the horizon	6×10^6	2×10^7
Sun at the zenith	2×10^9	6×10^9

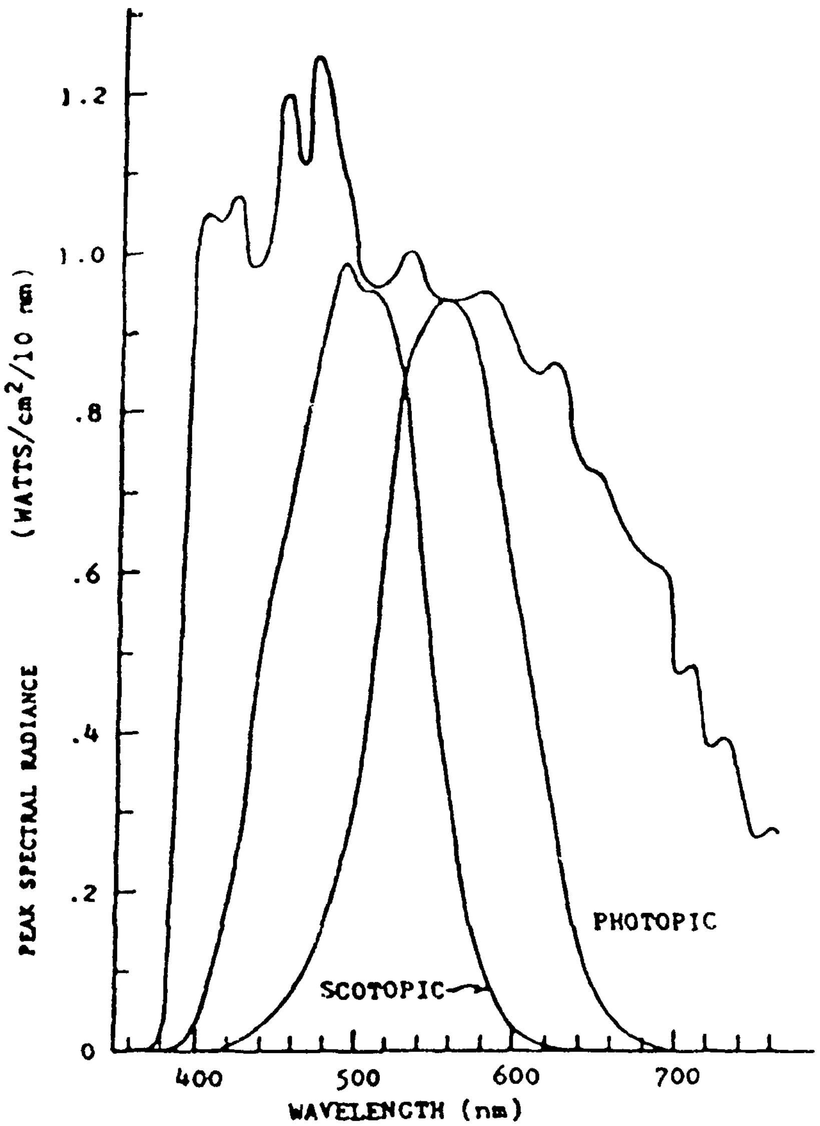

Figure 4. Xenon flash tube steradiancy through optical system and an infrared filter. The lower curves are the products of the luminosity factors and the spectral radiance.

TRANSMITTANCE OF THE OCULAR MEDIA

The luminosity factors include the spectral transmittance of the retinal photopigments. To correlate external stimuli with retinal processes, it is imperative that the actual quantity and direction of the light at the retina be known. This process is a very difficult problem and a number of efforts have been made to measure the absorption, scattering, and image-forming characteristics of the eye. The practical difficulties can be glimpsed from the wide variation in the results from different investigations.

One of the most serious practical difficulties is that the contents of the globe are either liquid or a soft gel. The scattering properties are a result of the cellular structures and minute inclusions; they will be drastically altered by small changes in the intraocular pressure, water content, and any other change from the normal physiological state. Another problem is the short focal length of the optical system of the eye. It is a relatively simple matter to measure the transmittance of a slab of material with polished parallel sides, but orders of magnitude more difficult to measure the spectral transmittance of a short focal length, diffusing optical system.

The three most frequently cited investigations will be briefly reviewed in an effort to define their ranges of applicability. Ludvigh and McCarthy (6) measured the direct transmittance through excised human eyes from subjects over 60 years old. They removed a small area of sclera, choroid, and retina from the back of the eye and covered the exposed vitreous with a cover slip. Twenty-one wavelength bands from 400 to 700 nm were selected by means of a monochromator and the signal from a photocell with and without the eye in place was used as the measure. The final data were corrected for the known yellowing of the lens with age and presented as representative values for young (21-year-old) subjects. The photocell sampled the area near the fovea and included only a portion of the scattered light, which for the older eyes used would have been significant.

Boettner and Wolter (7) measured the direct (limited to the image area) and the total transmission of the individual media: cornea, aqueous, lens, and vitreous. They arrived at the transmittance of the whole eye by combining the values for the individual components. They extended the wavelength region to an interval of 300 nm to 1.2 μm for monkey eyes and several human eyes ranging in age from 3 weeks to over 75 years. Their technique involved placing the components between parallel plates of glass and, in the case of the lens, applying pressure to flatten the poles.

Geeraets and Berry (8) measured the transmittance to the retina of whole excised eyes of humans, rabbits, and monkeys. They found that the only light lost through the preretinal media was that lost by reflection at the interfaces from 600 to 850 mm. The technique used ensured that the scattered as well as the imaged light was measured. The results from the three investigations for human eyes have been redrawn on one graph in Figure 5.

A portion of the disparity between the curves of Figure 5 can be attributed to the conditions of measurement. The two lower curves refer to light transmitted in the region of the source image. As such, they provide the appropriate values to use with the photopic luminosity factors which were found for a 2^0 field. The upper curves in the graph include the scattered portion of the transmitted light and correspond to large field viewing such as was used

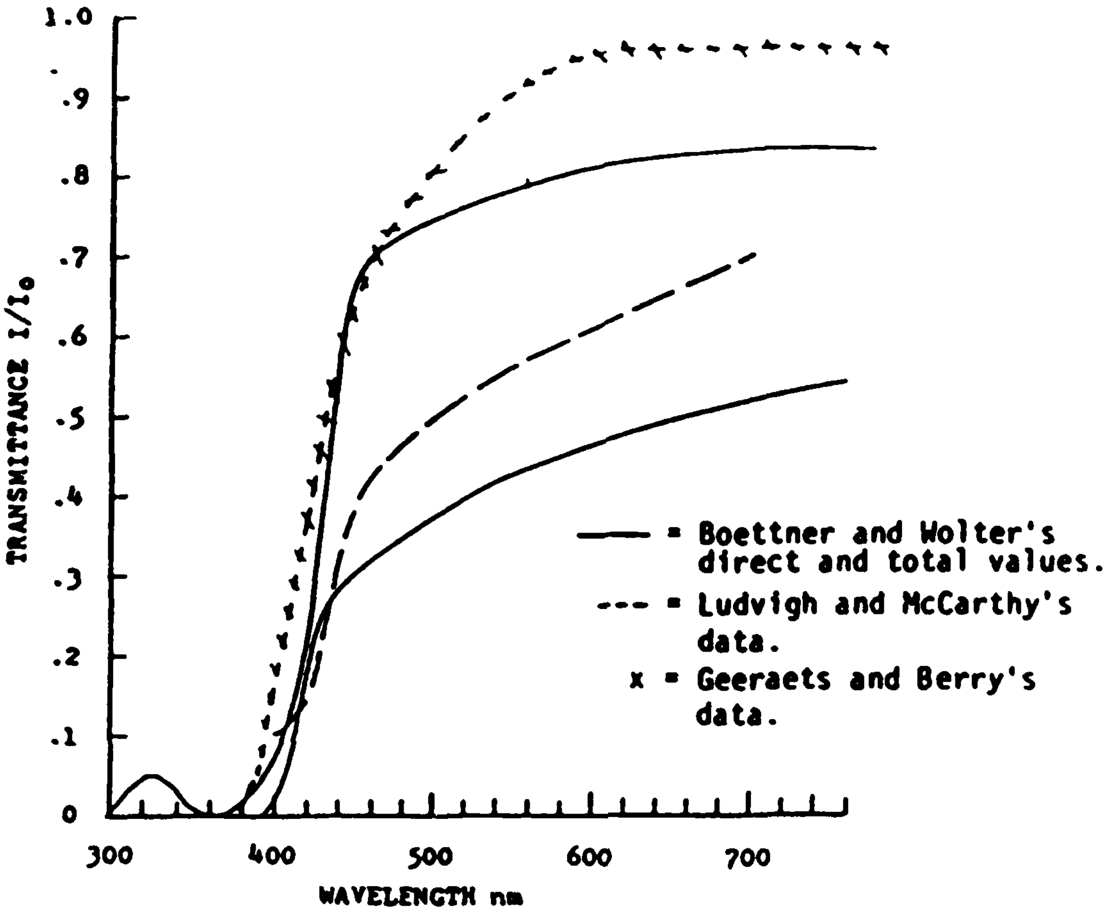

Figure 5. The transmittance of the preretinal ocular media as measured in three separate investigations.

for the scotopic luminosity factors. The magnitude of the discrepancy is disturbing, however, in view of the importance of the transmittance in correlating psychophysical studies with knowledge of retinal events from other disciplines.

The aqueous and vitreous humors have high transmittance, similar to water, through the ultraviolet (UV) and visible portion of the spectrum. The cornea begins to absorb at 310 nm and is nearly opaque to wavelengths shorter than 270 nm, while the lens is the principal site of absorption for wavelengths between about 400 and 300 nm. Fortunately, the transmittance of the lens can be assessed in vivo by using subjects who have had one or both lenses surgically removed but have normal retinal function. These subjects are called normal aphakics. Wald (9) measured the effect of the lens on the scotopic luminosity curve in this manner and found the aphakic sensitivity to be 1000 times that of the normal at 365 nm. Similar results were obtained by Wright (10).

The results of Wald and Wright do not necessarily mean that the lens has an optical density of 3.0. Normally, the retina is protected from UV by the lens, but if a freshly excised retina is kept dark adapted during preparation, then illuminated by UV light, it fluoresces strongly in the blue-green. Unilateral aphakics have reported that the color produced by light from 300 to 360 nm appears blue, thus indicating that the fluorescent light is used by the receptors. Since the color of the fluorescent light is near the luminosity peak, it is visually more effective than the exciting light. These facts contribute to an understanding of the color descriptions of Cerenkov radiation.

SPECTRA SENSITIVITY OF THE RETINA

The variability of the transmittance measurements sharply reduces the probability of using the luminosity factors to obtain a valid assessment of retinal spectral sensitivity. The necessary data can be obtained from measurements of the absorption characteristics of the retinal photopigments. Rhodopsin, the pigment of the rods, has been extensively studied and the absorption spectra from various species have been measured in solution. The absorption peaks for all mammals fall within a few nanometers. The cone photopigments have never been extracted from the human retina, probably because the cones account for only about 5% of the receptors.

Cattle rhodopsin is similar to human rhodopsin with the absorption peak at about 498 nm. The spectral absorption of cattle rhodopsin is shown in Figure 6 over the wavelength region from 250 to 600 nm (11). The spectral absorption consists of three peaks, in the visible, near UV, and UV. The absorption in the visible is similar in shape to the scotopic luminosity curve, except for the wavelength region where lenticular absorption is significant. The curve shows a sharp maximum at about 280 nm. This band is due to the protein and is similar in all retinal photopigments. The crosses on the curve represent the photosensitivity for bleaching for frog rhodopsin, scaled to match the absorption peak at 500 nm. As the crosses indicate, light absorbed in the protein band does not bleach the photopigment and, therefore, can be considered to be visually ineffective.

Extremely short wavelengths in the β-ray, γ-ray, and x-ray regions also produce visual stimulation (12,13). The effectiveness of ionizing radiation has been compared with that of light stimulation in several species, using the

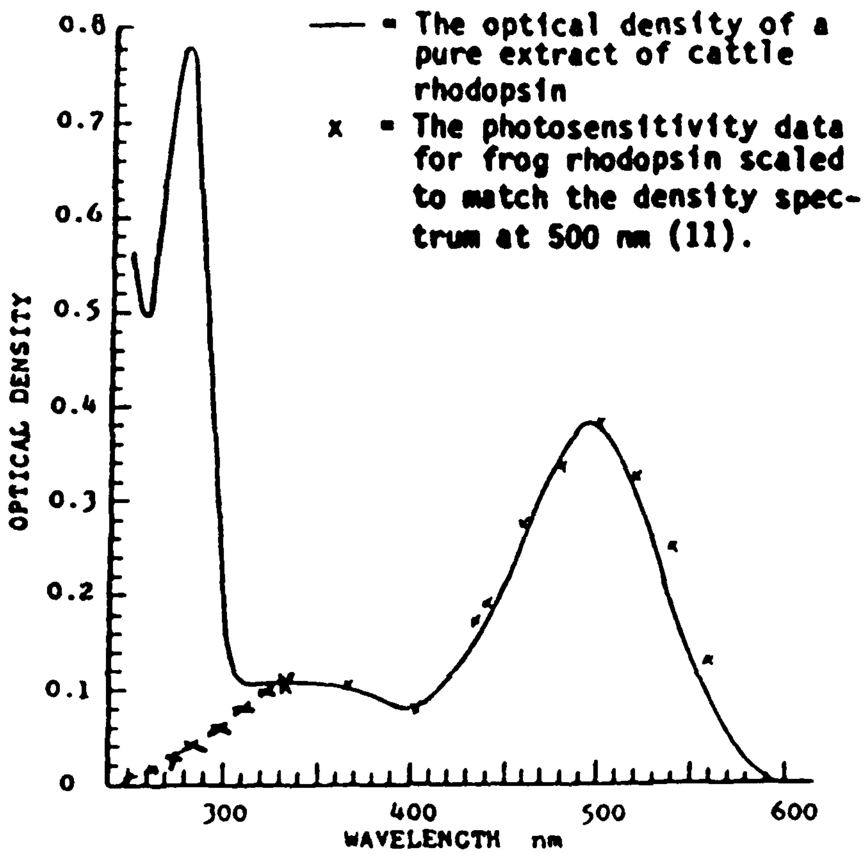

Figure 6. Spectral absorption of cattle rhodopsin.

electroretinogram (ERG) response. Dark adaptation following exposure to ionizing radiation and to light has been compared by recording the pigment migration in the eyes of moths (14). These studies provide us with an estimate of the retinal sensitivity to short wavelengths relative to that for visible light. The mechanism underlying the visual response to ionizing radiation is not as well known as in the case of the photopigment response to visible and near UV radiation.

The density spectrum of cattle rhodopsin is replotted in Figure 7 with the spectral sensitivity of the aphakic (15,16). The sensitivity was determined by electroretinography. The aphakic sensitivity in the figure has been corrected by the transmittance of the cornea (crosses) and, as such, refers to light at the retina.

The curves are plotted on an equal quantum basis unlike the luminosity factors which refer to an equal energy spectrum. The similarity between the density spectrum for rhodopsin and the sensitivity to external flashes at the different wavelengths is striking. In the case of the relatively low density of rhodopsin in the human rods, the density spectrum and the absorption spectrum can be shown to be essentially identical (4).

The use of the ERG in assessing the visual effectiveness of the spectral bands is especially helpful in comparing the results with Cerenkov radiation. The ERG responds to the total light in the eye and can be elicited with light imaged on the optic disc. In such a case, the ERG is responding to scattered light only and, therefore, is similar to the effect of the diffuse Cerenkov radiation. The values from Figure 7 will be used as the scotopic luminosity factors in evaluating the luminous flux from Cerenkov radiation from electron beams.

EFFECTS OF CERENKOV RADIATION

The data in Figure 7 for the spectral sensitivity to an equal quantum spectrum at the retina can be combined with the quantal distribution of Cerenkov radiation in Figure 3 to find the equivalent number of quanta at 507 nm. The calculation yields the value of 106 equivalent quanta of 507 nm/cm of path length through the aqueous and vitreous for each electron of 6 MeV or greater.

To develop the predictive model of the electron beam induced flash effects, we will use a simplified model of the eye. We will assume a thin spherical shell, 2.4 cm in diameter, filled with aqueous and vitreous humors. While the calculations for Cerenkov radiation showed a 13% increase in quanta per unit path length in the central lens, its thickness is of the order of 2 mm, and the difference will be ignored. The average path length in the sphere can be found by equating the volume of a cylinder of the same radius, r, and height, h,

$$h\pi r^2 = 4/3\pi^2 = 4/3\pi r^3 \qquad (13)$$

and solving for h. This gives the average path length of 1.6 cm in the eye, assuming that the electron beam is an equispaced array of particle paths. Therefore, the average yield per electron in terms of effective light is

$$1\ e^- = 170 \text{ equivalent quanta of } 507 \text{ nm.} \qquad (14)$$

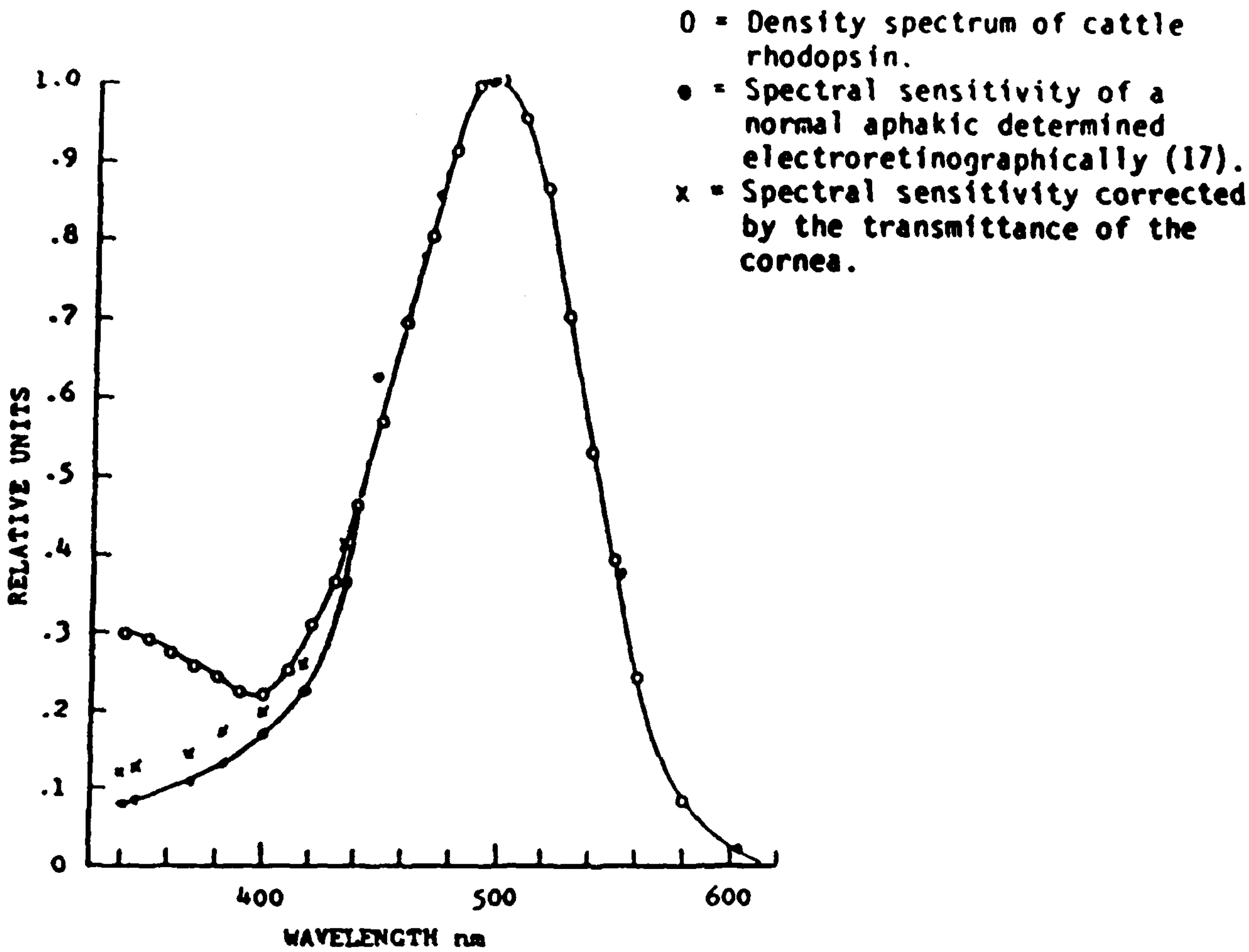

Figure 7. Scotopic luminosity factors.

It has been experimentally determined that the number of accelerated particles in the electron beam can be expressed by the relation

$$1 \text{ rad} \approx 2.3 \times 10^7 \ e^-/cm^2 \qquad (15)$$

The cross-section area intercepted by the spherical shell is 4.5 cm^2. Therefore, the number of equivalent 507 nm quanta produced in the eye by an electron beam can be calculated from the relationship

$$1 \text{ rad} \approx 1.76 \times 10^{10} \text{ equivalent q of 507 nm.} \qquad (16)$$

A further simplifying assumption will be made, namely that all quanta generated will reach the back hemisphere of the globe or will cover 2π steradians. This process leads to the relationship

$$1 \text{ rad} \approx 2.8 \times 10^9 \text{ equiv. q/sr of 507 nm.} \qquad (17)$$

We now have the necessary data to allow a comparison with the retinal illuminance values from external sources. We found that 1 scotopic td is equivalent to 1.46×10^9 q/sec/sr of 507 nm (Equation 11). The total transmittance of the ocular media at 507 nm can be found by taking the average of the two upper curves in Figure 5. The average value is 0.8, therefore, for external light sources

$$1 \text{ scotopic td} = 1.17 \times 10^9 \text{ q/sec/sr of 507 nm} \qquad (18)$$

at the retina. The above value refers to a steradian of visual angle, whereas, the steradian of equation 17 refers to the areas of the globe. The posterior nodal distance of the eye is about 1.67 cm, and we have assumed the value of 1.2 cm for the radius of the globe. Combining equations 17 and 18 with the correction for the areas of the unit solid angles, yields the desired relationship for converting the electron beam induced Cerenkov radiation to retinal exposure,

$$1 \text{ rad} \approx 4.6 \text{ scotopic td}\cdot\text{sec.} \qquad (19)$$

There seems to be no existing data on the absolute threshold for a ganzfeld for exposures as brief as 1 µsec. With some assumptions concerning temporal and spatial summation, we can extrapolate the existing data. The estimated value is 2×10^{-5} scotopic td·sec. Based on these calculations for Cerenkov radiation, absolute visual threshold corresponds to a total dose of about 4.3 µrad. This value for visible and near UV light can be compared with 0.5 mrad exposure to x-rays for threshold visual response with whole retina stimulation (18).

A similar calculation for cone sensitivity yields the conversion factor

$$1 \text{ rad} \approx 9.95 \times 10^8 \text{ equiv. q of 555 nm/sr.} \qquad (20)$$

From equation 18 and the transmittance of the eye media at 555 nm,

$$1 \text{ photopic td} = 3.5 \times 10^9 \text{ q/sec/sr of 555 nm} \qquad (21)$$

at the retina. Thus $1 \text{ rad} \approx 0.55 \text{ photopic td}\cdot\text{sec.} \qquad (22)$

Equations (19) and (22) provide the conversion factors for a direct comparison of whole eye exposures to relativistic electron beams with flashblindness studies. A large body of data is available on foveal recovery times following flash energies of the magnitude anticipated in nuclear weapon detonations; i.e., from 10^4 to 10^7 photopic td·sec. In the low photopic range of adaptation, a flash of 3×10^4 photopic td·sec results in approximately 1 sec recovery time for a 0.31 visual acuity grating of 1.5-mL luminance (19). The recovery times double for parafoveal acuity targets for 60° flash fields compared with 2° fields. Foveal recovery times are not sensitive to field size changes (20). The existing data indicate that under photopic light levels, the electron beam flux would have to be of the order of 10^5 rads to cause a measurable decrement in visual performance for instrument reading or similar tasks.

Under scotopic adaptation levels, much smaller flash energies produce measurable changes in peripheral sensitivity. An exposure of 1.7 scotopic td·sec in an area 2° from the fovea resulted in a measurable decrease in sensitivity, while exposures ten times greater in the area from 6° to 18° from the fovea had no measurable effect (21). However, this result implies that whole eye exposures to a 10-rad electron beam might cause an interruption of a few seconds in the dark-adapted eye for the detection of peripheral targets.

CONCLUSIONS

Practical difficulties arise in applying our existing data on flashblindness or transient adaptation to a predictive model of similar phenomena resulting from Cerenkov radiation, produced within the eye by relativistic particles. The spatial distribution of the Cerenkov photons results in most of the light entering the receptors at a large angle to their axes. The retinal direction effect, or Stiles-Crawford effect, results in a reduced effectivity for light under such conditions, particularly in the cones. However, the rods will exhibit some directional effect for large angles of entry. The Stiles-Crawford effect has been neglected in the simplified model used in this report, and it may reduce the effectiveness of the Cerenkov radiation by as much as a factor of ten.

The spectral characteristics of the Cerenkov radiation have been evaluated and converted to equivalent retinal irradiance from external sources. On the basis of the conversion, electron fluxes have been estimated for 2-sec recovery times from flashblinding. The electrons are assumed to have energies >6 MeV and to be delivered in 1 or more bursts of 1 μsec each over 1 sec. It is important to note that very little data exists on recovery times as short as 2 sec for either photopic or scotopic conditions. This situation is a direct result of the lack of definition of the critical tasks and their sensitivity to an interruption of background adaptation.

The Cerenkov radiation produced within the eye by relativistic electrons can be compared to light from external sources by the relationships:

$$1 \text{ rad} = 4.6 \text{ scotopic td·sec} \qquad (23)$$

and

$$1 \text{ rad} = 0.55 \text{ photopic td·sec.} \qquad (24)$$

Based on these conversion factors, the following estimates can be derived by extrapolation from existing data:

1. Absolute threshold is equivalent to the Cerenkov radiation from a 4.3-μrad electron beam and to a 0.5-mrad x-ray beam.

2. For low photopic levels of adaptation (approximately 10 td), 10^5-rad electron beam would be required for a 2-sec recovery time for foveal or parafoveal vision.

3. For the dark-adapted eye, a dose of 10 rads may cause a 2-sec interruption in the detection of low-contrast, peripheral targets.

REFERENCES

1. Frank, I., and I. Tamm. Cited in Price, W. J., Nuclear Radiation Detection, p. 289, New York: McGraw-Hill Book Co., Inc., 1964. Compt Rend (Doklady) Acad Sci URSS 3:109 (1937).

2. Miller, N. D. Unpublished results from chromatic aberration model.

3. Pinegin, N. I. Uber die Absolute Empfindlichkeit des Auges im Ultravioletten und im Sichtbaren Spektrum. Compt Rend (Doklady) Acad Sci URSS 30:206-211 (1941).

4. Pirenne, M. H., F. H. C. Marriot, and E. F. O'Doherty. Individual differences in night-vision efficiency. Spec Rep Ser Med Res Coun, London, p. 294 (1957).

5. Luria, S. M. Absolute thresholds for extremely wide fields. J Opt Soc Am 48:884-886 (1958).

6. Ludvigh, E., and E. F. McCarthy. Absorption of visible light by the refractive media of the human eye. Arch Ophthal 20:37-51 (1938).

7. Boettner, E. A., and J. R. Wolter. Transmission of the ocular media. Invest Ophthal 1:776-783 (1962).

8. Geeraets, W. J., and E. R. Berry. Ocular spectral characteristics as related to hazards from lasers and other light sources. Am J Ophthal 66:15-20 (1968).

9. Wald, G. Human vision and the spectrum. Science 101:653-658 (1945).

10. Wright, W. D. The visual sensitivity of normal and aphakic observers in the ultraviolet. Annee Psychol 50:169-177 (1951).

11. Dartnell, H. J. A. Structure of visual pigments, p. 429. In The Eye II, H. Davson (Ed). New York: Academic Press, 1962.

12. Lipetz, L. E. The X-ray and radium phosphenes. Brit J Ophthal 39:577-598 (1955).

13. Bachofer, C. S., and S. E. Wittry. Comparison of electroretinal responses to x-ray and to light. Radiat Res 17:1-10 (1962).

14. Schafer, K. L. Receptor sensitivity and pigment migration to ionizing radiation and light in the noctuid moth. Visual Psychophys and Physiol 93:106 (1978).

15. Collins, F. D., R. M. Love, and R. A. Morton. Studies in rhodopsin 4. Preparation of rhodopsin. Biochem J 51:292-298 (1952).

16. Dodt, E., and J. B. Walther. Fluorescence of the crystalline lens and electro-retinographic sensitivity determinations. Nature (London) 181:286-287 (1958).

17. Dartnall, H. J. A. Visual pigments in photoreceptors, p. 513. In The Eye II, H. Davson (Ed). New York: Academic Press, 1962.

18. Pape, R., and J. Zakovsky. Die roentgen-strahlen-sensibilitat der retina. Fortschr Geb Roentgenstr 80:65-71 (1954).

19. Chism, G. T., and J. H. Hill. Flashblindness: The effects of preflash adaptation and pupil size. Aerospace Med 38:395-399 (1967).

20. Chism, G. T. Intraocular effects on flashblindness: II. Parafoveal Recovery. Aerospace Med 42:31-35 (1971).

21. Wulfeck, J. W., A. Weisz, and M. W. Raben. Vision in military aviation. Wright Air Development Center (WADC) TR-58-399 (AD 207780), 1958, Wright-Patterson AFB, OH.

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